Risk Assessment Framework for Geologic Carbon Sequestration Sites

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Abstract: We have developed a simple and transparent approach for assessing CO_2 and brine leakage risk associated with CO_2 injection at geologic carbon sequestration (GCS) sites. The approach, called the Certification Framework (CF), is based on the concept of effective trapping, which takes into account both the probability of leakage from the storage formation and impacts of leakage. The effective trapping concept acknowledges that GCS can be safe and effective even if some CO_2 and brine were to escape from the storage formation provided the impact of such leakage is below agreed-upon limits. The CF uses deterministic process models to calculate expected well- and fault-related leakage fluxes and concentrations. These in turn quantify the impacts under a given leakage scenario to so-called "compartments," which comprise collections of vulnerable entities. The probabilistic part of the calculated risk comes from the likelihood of (1) the intersections of injected CO_2 and related pressure perturbations with well or fault leakage pathways, and (2) intersections of leakage pathways with compartments. Two innovative approaches for predicting leakage likelihood, namely (1) fault statistics, and (2) fuzzy rules for fault and fracture intersection probability, are highlighted here.

Keywords: Geologic carbon sequestration, leakage risk assessment, fuzzy rules, fault statistics

1. INTRODUCTION

Although geologic carbon sequestration (GCS) is being considered to alleviate one of the most serious global environmental threats ever encountered by mankind, namely the build-up of carbon dioxide (CO_2) in the atmosphere due largely to fossil fuel combustion, GCS itself involves environment risk to the immediate areas surrounding GCS sites [1]. These hazards include leakage of CO_2 and/or brine into resources such as potable groundwater, hydrocarbon and mineral resources, or into the near-surface environment. Determining the likelihood and consequences of leakage of CO_2 and brine are complicated in GCS systems due to:

- inherent uncertainty of subsurface properties that control flow and transport of fluids;
- lack of experience and track record with GCS systems given the novelty of the technology;
- coupled nature of flow, transport, geochemical, and geomechanical processes;
- relatively benign nature of CO_2 and corresponding subtlety of leakage consequences;
- need for consideration of long time horizon for consequences.

Furthermore, quantifying and communicating environmental risks of GCS to a wide variety of global and local stakeholders in a way that allows balancing the benefits of GCS against the costs and risks is a fundamental need for acceptance of GCS.

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The considerations above led our group to develop a leakage risk assessment approach called the Certification Framework (CF) that is tailored to the special needs and challenges of GCS systems [2, 3]. In this paper, we summarize briefly the definitions, concepts, and methods used in the CF, and then describe in more detail two of the specialized methods being developed primarily by two of us (Jordan [4] and Zhang [5]) for handling uncertainty related to leakage through faults and fractures. Other components and methods of the CF have been described elsewhere [2, 3].

2. OVERVIEW OF CF DEFINITIONS AND METHODS

The purpose of the CF is to provide a framework for project proponents, regulators, and the public to analyze the risks of geologic carbon sequestration in a simple and transparent way to certify start up and decommissioning of geologic CO_2 storage sites. The CF currently emphasizes leakage risk associated with subsurface processes and excludes compression, transportation, and injection-well leakage risk. The CF is designed to be simple through the use of (1) proxy concentrations or fluxes for quantifying impact rather than complicated exposure functions, (2) a catalog of pre-computed CO_2 injection results, and (3) a simple framework for calculating leakage risk. For transparency, the CF endeavors to use a clear and precise in terminology in order to communicate to the full spectrum of stakeholders. The definitions are presented below, followed by brief description of the framework structure.

Definitions

- Effective Trapping is the overarching requirement in the CF for safety and effectiveness.
- Storage Region is the 3D volume of the subsurface intended to contain injected CO_2.
- Leakage is migration across the boundary of the Storage Region.
- Compartment is a region containing vulnerable entities (e.g., environment and resources).
- Impact is a consequence to a compartment, evaluated by proxy concentrations or fluxes.
- Risk is the product of probability and consequence (impact).
- CO_2 Leakage Risk is the probability that negative impacts will occur to compartments due to CO_2 migration.
- Effective Trapping implies that CO_2 Leakage Risk is below agreed-upon thresholds.

Compartments and Conduits

In the CF, impacts occur to compartments, while wells and faults are the potential leakage pathways. Figure 1a shows how the CF conceptualizes a generic system into source (CO_2 injection), conduits (wells and faults), and compartments HMR, USDW, NSE, HS, and ECA, where

- HMR = Hydrocarbon and Mineral Resource
- USDW = Underground Source of Drinking Water
- NSE = Near-Surface Environment
- HS = Health and Safety
- ECA = Emission Credits and Atmosphere

By these simplifications, the CF is a top-down approach that assumes a priori what the main risk issues are.

Risk and Flow Chart

In Figure 1b, the dotted lines connecting the source (CO_2) to the conduits (wells and faults), and conduits to the compartments, show the concept of likelihood of the CO_2 source intersecting conduits, and the conduits likelihood of intersecting compartments. In the CF, the probability of CO_2 leaking from the source to a compartment is the product of these intersection probabilities. Figure 2 shows a flow chart of CF logic and inputs and outputs. As shown, site characterization data define the model storage system which is then simulated to estimate plume size, pressure rise, migration, and trapping.

One of the main challenges of estimating CO_2 and brine leakage risk is dealing with incomplete knowledge of faults and fractures in the subsurface that may provide leakage pathways to the compartments. This information informs the inputs needed in Figure 2 related to probability of a plume intersecting conduits, and conduits intersecting compartments. In the remainder of this paper, we summarize two approaches we have taken to address this challenge. Other components of the CF involving the catalog of simulation results, wellbore flow modeling, and dense gas dispersion are presented elsewhere [2, 3].

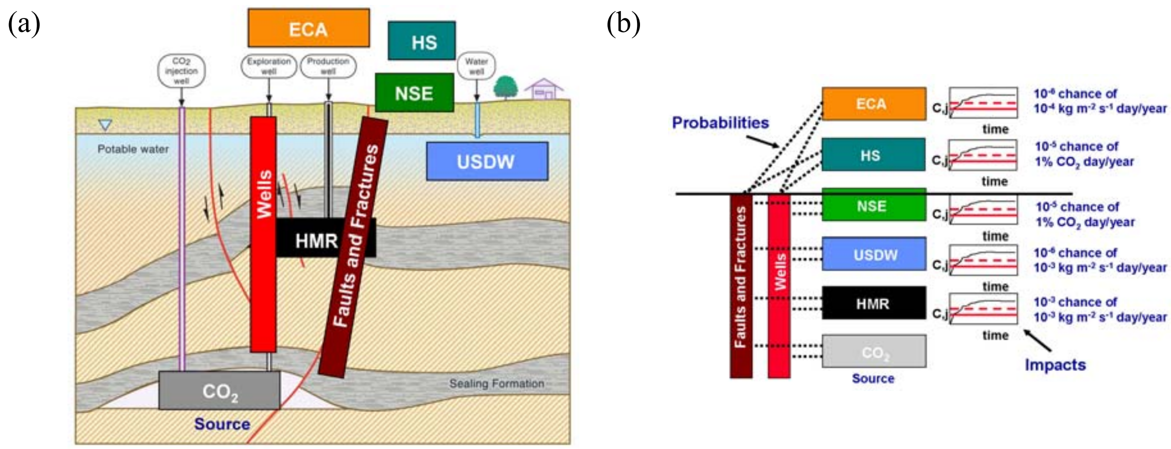

Figure 1. Generic schematic of compartments and conduits in the CF (a), and its abstraction into a leakage risk schematic (b).

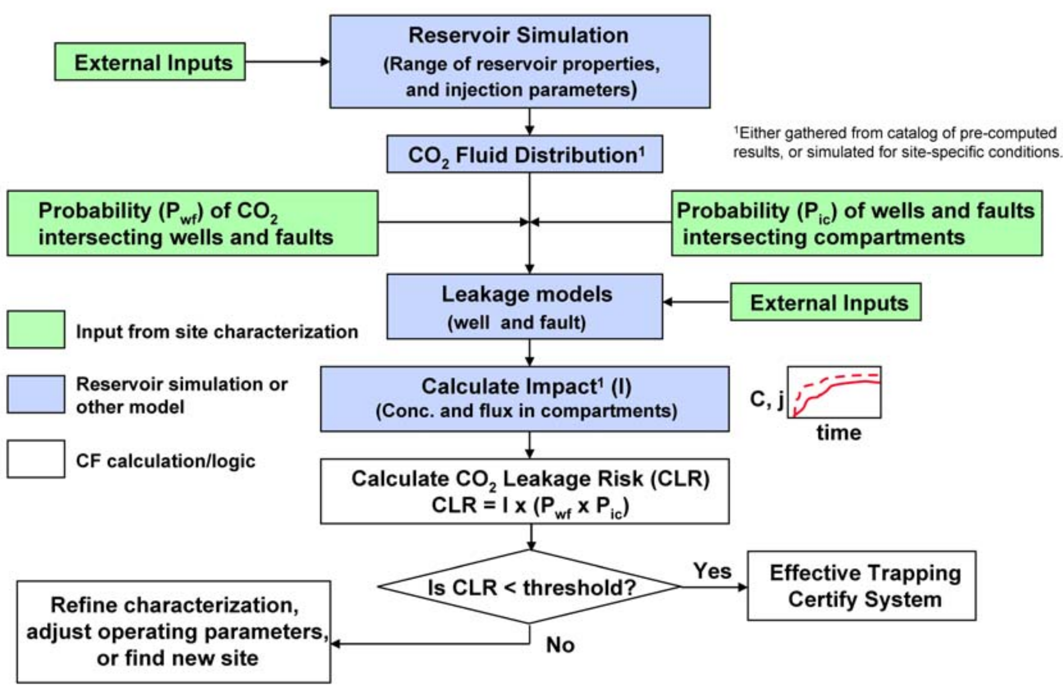

Figure 2. Flow chart of CF process showing logic and inputs and outputs.

3. FAULT POPULATION STATISTICS

In some cases, faults will behave as conductive features that could be responsible for leakage of CO_2 or brine. Leakage risk assessment requires an estimate of the likelihood that the CO_2 or the pressure rise in the brine will encounter faults that are either (1) large enough to be of concern for leakage by virtue of their intrinsic properties (e.g., localized high-permeability due to large fracture apertures or presence of a permeable shear zone), or (2) have offset large enough to render cap-rock sealing layers discontinuous and therefore make them vulnerable to leakage. As this discussion suggests, fault size is the key property that controls the potential for fault leakage. One of us (Jordan) has developed a method based on fault population statistics derived from available fault coverages (geologic or structure maps) near or at a prospective site [4]. Combining the measured statistics with model estimates of the CO_2 plume or pressure perturbation size, both of which will be hereafter referred to as plume size for brevity, allows calculation of the probability of the plume encountering a fault of a particular size.

The method begins with the knowledge that the areal density of faults, *F*, typically follows a power-law distribution from low to moderate strains of the form

$$F \propto d^{-C_d} \tag{1}$$

which implies

$$\log F \propto -C_d \log d \tag{2}$$

where F is the areal density of faults with displacement greater than d, and C_d is the power law exponent [4]. Values of F can be accurately calculated by measuring the length of faults with greater than a certain displacement in an area and dividing by the area. Structure contour maps are a typical source for such data. The linear relation between log F and log d implies that there is a high density of small faults and low density of large faults. As the large faults are the ones of concern, we can compare the areal density of faults of a certain size to the size of the plume to estimate the probability that the plume will intersect faults of a size large enough to be of concern. This discussion assumes implicitly that actual data on mapped faults (of a given size) at the particular GCS site are lacking, thus the reliance on statistical properties of faults gathered from a nearby or analogue site.

To calculate F for a given d, the total length of the fault segments with displacement greater than d (displacement cutoff) must be calculated from multiple measurements made from fault coverage(s), e.g., from oil or gas field structure maps, gas storage facility structure maps, or regional geologic maps. Log-log plots are constructed of fault density versus displacement cutoff as shown in Figure 3 for the southern San Joaquin Valley, California, example. Note this example uses vertical offset instead of displacement because most of the faults in the area are nearly vertical normal faults. As shown in Figure 3, the data fit a power-law distribution for the larger offsets, with deviation at lower offset values. This effect arises from the inherent resolution limitations of fault mapping, namely, many small faults are overlooked and ignored, either intentionally, or simply because the resolution of various characterization techniques (e.g., seismic reflection) is too low to discern them.

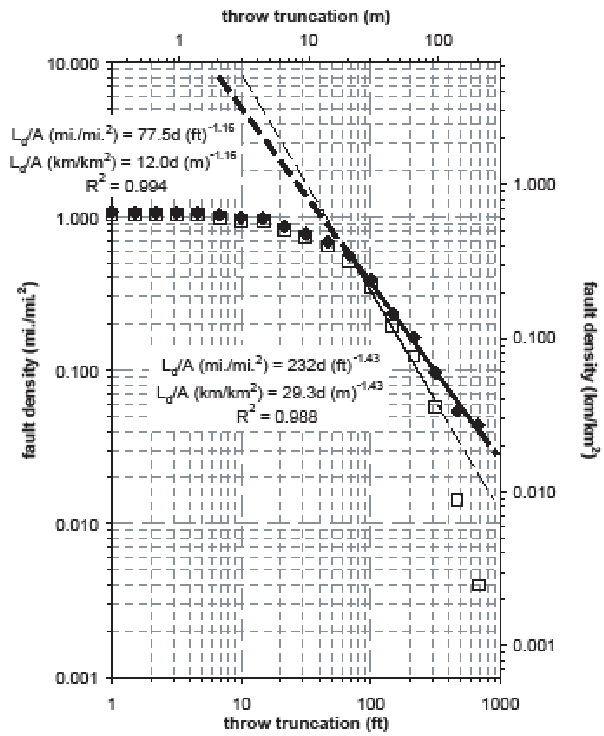

Figure 3. Measured data on vertical offset (throw truncation) and fault density for a site in the southern San Joaquin Valley, California. Open boxes are raw data and filled boxes are data adjusted to account for the "finite-range effect."

Calculating Plume Fault Encounter Probability

Referring to Figure 4, which shows 100 randomly located plumes and a single randomly located fault of size L_f, the probability, g, of the plumes intersecting a fault is given by

$$\Pr(g) = A_f / A_0 \tag{3}$$

where A_0 is the area of interest and A_f is the area of the fault. If a plume is centered within a distance equal to the plume radius, r, the plume will intersect the fault (an event represented by g) providing a rationale for defining the area of the fault relevant to plume intersection as

$$A_f = 2rL_f \tag{4}$$

where L_f is the length of fault in the study area (shown as L on Figure 4). L_f can also be written as the areal fault density F times A_0:

$$L_f = FA_0 \tag{5}$$

Substituting Equation 5 into 4, 4 into 3, and canceling terms gives

$$\Pr(g) = 2rF \tag{6}$$

This approach assumes that the fault or faults cross the entire area of interest (A_0), and that each plume only encounters one fault. The first condition is equivalent to assuming that faults are large relative to A_0, and the second condition is equivalent to assuming the spacing between faults is large relative to the plume diameter. As the spacing between large faults is generally greater than between small faults, these assumptions are qualitatively in agreement. The value of F is measured from fault maps (as discussed), and the value of r can be approximated by numerical simulation. If the plume margin is some shape other than circular, then Equation 6 can be generalized to any plume shape by substituting half the plume dimension perpendicular to the fault, s:

$$\Pr(g) = 2sF \tag{7}$$

The value of s can be measured directly from plots of the area swept by mobile CO_2 as modeled by numerical simulation.

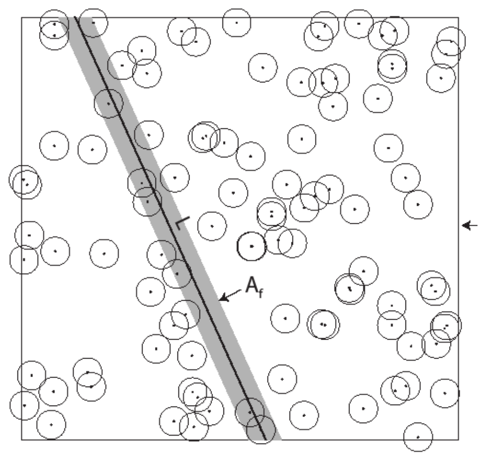

Figure 4. Diagram of 100 randomly located, circular plumes, and a randomly located fault. Any plume geometrically centered within the shaded area will encounter the fault.

If the relationship between F and d is power law, then

$$\Pr(g) = 2sBd^{-C_d} \tag{8}$$

where B is a proportionality constant. For elliptical plumes, the plume dimension perpendicular to the fault (s) can be calculated from the plume area, aspect ratio (eccentricity), and the acute angle between the long axis of the plume and the fault orientation of interest [4].

This approach was used for an actual site in the southern San Joaquin Valley, California, where numerical simulation indicated the CO_2 plume would be elliptical due to the dipping reservoir. The sealing formation over the storage target at the site has a vertical thickness of approximately 180 m (590 ft). A throw truncation equal to the seal thickness is one threshold of concern (although such a fault may not be a leakage conduit if it has intrinsic sealing properties). The adjusted fault density equation on Figure 3 indicates the average fault density, F, at this throw truncation is 0.028 km/km^2 (0.046 mi./mi.^{2}). This is a low density, so the condition that the fault-perpendicular plume dimension is much smaller than the spacing between faults is sufficiently met to use the probability estimation of Equation 7. The distribution of Pr(g) at this fault density and simulated plume area, but varying plume aspect ratios and orientations, is shown on Figure 5. The simulated plume has an aspect ratio of 1.32 and a plume axis to predominant fault angle of 70°. Given these values, Figure 5 suggests the Pr(g) for a fully seal-offsetting fault would be 3.3%.

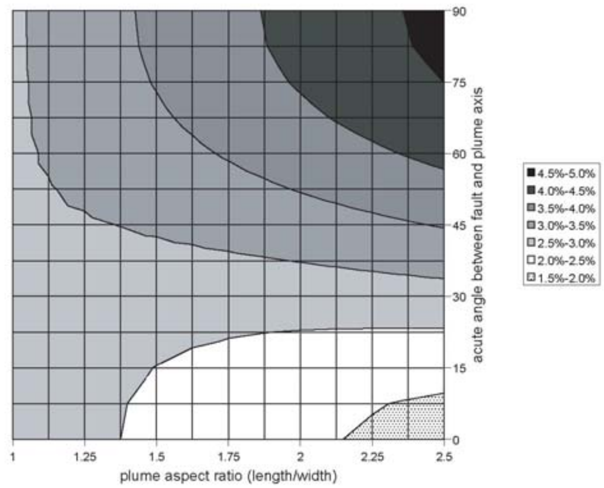

Figure 8. Probability contours that the southern San Joaquin Valley plume will encounter a fault fully-offsetting the seal as a function of the plume aspect ratio and the angle between the plume axis and the fault.

4. PROBABILITY OF FAULT CONNECTIVITY

The above approach addresses the probability that the plume will intersect a fault of a given size. While leakage may occur through such a fault, such leakage does not imply that CO_2 or brine will be conveyed to a compartment containing vulnerable entities which tend to be distant from the storage region (e.g., USDW, or NSE). For transport of CO_2 or brine long distances upward through sedimentary formations, it may be necessary for several different faults to be connected to form a fault or fracture network. Here we describe an approach developed by one of us (Zhang) to calculate P_{leak}, the probability that a CO_2 plume will encounter a system of faults or fractures that is connected to a compartment that may be impacted by leakage [5]. The fundamental problem addressed by the approach is presented graphically in Figure 9, which depicts the uncertainty in connectivity of faults or fractures in the subsurface. However, there is additional uncertainty about the location and size of the CO_2 plume, and the properties of the various faults and fractures, all of which must be incorporated into the estimated leakage risk.

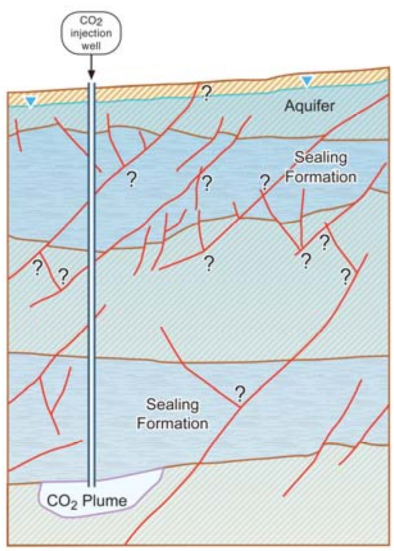

Figure 9. Schematic geologic cross section (not to scale) showing CO_2 injection well, CO_2 plume, reservoir, sealing formation, overlying formations, and potable ground water, along with conductive faults that may or may not intersect as indicated by the question marks.

Overview of Methodology

The approach includes four steps:

(1) estimate a critical value (α_c) of the parameter α (related to the density of faults and fractures) such that when this critical value is reached, the system is on average connected between the storage formation and a compartment;
(2) estimate the probability that the CO_2 plume will encounter the connected conduits for a system with $\alpha \geq \alpha_c$,;
(3) construct fuzzy rules that relate information about the conduit system and CO_2 plume size to leakage probability; and
(4) for given system characteristics, predict the probability that leakage will occur from the storage formation to a compartment through connected conduits.

The approach assumes (1) a square, two-dimensional cross sectional system of dimension L x L, (2) faults/fractures are randomly oriented and positioned, (3) faults/fractures are uniformly conductive, and (4) faults/fractures follow a power-law length distribution. Below we outline the steps.

Estimation of Critical Value α_c

Fault length distributions are often described by the power-law distribution [6]:

$$n(l, L) = \alpha(L) l^{-a} \qquad (9)$$

where $n(l, L)dl$ is the number of faults having a length in the range [l, $l+dl$], $\alpha(L)$ is a coefficient of proportionality that reflects fault density and depends on the system size L, and a is an exponent, which typically varies between 1 and 3.

In percolation theory [7], a parameter p is used as an average measure of the geometric properties, generally related to the density of elements, which also provides information on the connectivity of the system. The percolation threshold p_c is defined as the critical p value below which (on average) the fault system is not connected, while when p is above the critical value p_c, the system is connected. In other words, 50% of the systems at the percolation threshold are connected. Bour and Davy [7] presented an analytical expression for the percolation threshold for a fault system following a power-law length distribution as:

$$p_c(L) = \int_{l_{\min}}^{L} \frac{\alpha_c(L) l^{-a} l^2}{L^2} dl + \int_{L}^{l_{\max}} \alpha_c(L) l^{-a} dl \qquad (10)$$

If $l_{max} < L$, the second term on the right-hand side drops out and the first term integrates to l_{max} instead of L. For a given system, we can calculate the critical parameter $\alpha_{cs}(L_s)$ (i.e., when $p(L) = p_c(L)$) and compare it to the actual parameter $\alpha_s(L_s)$. If the actual density is much smaller than the critical value, we can conclude that the system is not connected and the CO_2 plume will not be able to leak out through the fault system.

Generation of Conduit Network

The approach to estimate the probability that a CO_2 plume will escape through the connected conduits and reach compartments for a system with $\alpha(L) > \alpha_c(L)$ requires generation of discrete fracture networks. Uncertainty from lack of knowledge of the system properties is considered by using fuzzy-rule-based modeling to propagate the uncertainty of the input parameters in estimating P_{leak} (2) Monte Carlo simulation is used to address the different connectivities in the fracture network even for systems with the same parameters (e.g., system size and fracture distribution). Uncertainty in the size and location of the CO_2 plume is addressed by varying CO_2 plume size and using a moving average to consider the uncertain location of the plume.

The parameters varied in the fracture network generation and P_{leak} calculations are the normalized system size L_s, the normalized maximum fracture length $l_{max\,s}$, the exponent a, the ratio of $\alpha_s(L_s)/\alpha_{cs}(L_s)$, and the normalized plume size M_s (all normalized by the smallest fracture size).

For each of the realizations of the Monte Carlo-generated network, the outcome has the following format:

IF $L_s = L_1$, $l_{max\,s} = l_1$, $a = a_1$, $r = \alpha_s(L_s)/\alpha_{cs}(L_s) = r_l$, and $M_s = M_1$
THEN the probability that a CO_2 plume escapes from the storage reservoir through a connected network of conduit (P_{leak}) is b.

where L_1, l_1, a_1, r_1 ($r_1 \geq 1$), and M_1 are the numerical values of the varying parameters in the simulation (crisp numbers) which should cover all possible values considered.

Construction of Fuzzy Rules for Calculating P_{leak}

Fuzzy set theory, introduced by Zadeh [8], has been used to deal with approximate (rather than exact) reasoning. In a fuzzy statement, A_i is a fuzzy number that reflects vagueness quantified by membership functions with triangular, trapezoid, or Gaussian forms. Fuzzy rules can be used to model systems with imprecise or uncertain information. These rules can be developed using expert opinions, existing data, and qualitative information. Alternatively, fuzzy rules can be generated through numerical simulations. In the approach described here, we use results from the Monte Carlo fault network generation as a training set to construct fuzzy rules of connectivity.

An example of a fuzzy-rule statement using triangular membership functions is as follows (the numbers in this statement are dimensionless numbers that are normalized with respect the smallest fracture size):

IF $a = (1.1, 1.5, 2.0)$ AND $L_s = (50, 100, 200)$ AND $l_{maxs} = (50, 100, 200)$
AND $r = (0.75, 1.0, 1.25)$ AND $r_p = (0.2, 0.4, 0.6)$
THEN $P_{leak} = (0.01, 0.12, 0.18)$

where $r_p = M_s/L_s$. Using the centroid method, the final defuzzified P_{leak} for this rule (when it is fulfilled) is 0.1.

Calculation of P_{leak} for a Given System

The first step is to calculate the critical $\alpha_{cs}(L_s)$ and compare it to $\alpha_s(L_s)$. If the latter is smaller, P_{leak} = 0 and no further calculation needs to be done. Otherwise, the above fuzzy rules are used to infer P_{leak}. To demonstrate the approach, we use fuzzy rules to predict P_{leak} as a function of r_p (CO_2 plume size divided by system size) for a system with a of approximately 1.5, $l_{max\,s}$ of approximately 100, L_s of approximately 100, and a few values of $r = \alpha_s(L_s)/\alpha_{cs}(L_s)$. The final defuzzified P_{leak} are shown in Figure 10. Details of the method are presented in Zhang et al. [17]. In brief Figure 10 shows that the probability of leakage increases for larger plumes size (M_s) and for larger degree of connectivity as represented by the ratio of $\alpha(L)$ to the critical $\alpha_c(L)$.

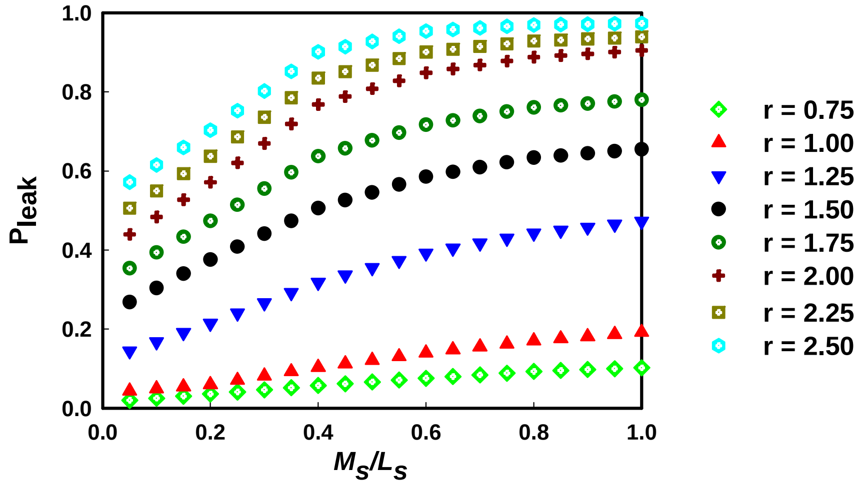

Figure 10. Fuzzy-rule based prediction of P_{leak} as a function of normalized CO_2 plume size for a system with $a = 1.5$, $l_{max\ s} = 100$, $L_s = 100$, and different values of $r = \alpha_s(L_s)/\alpha_{cs}(L_s)$.

Conclusions

We have developed a framework called the Certification Framework (CF) for leakage risk assessment of geologic carbon sequestration sites. The CF is designed for GCS sites to handle the expected lack of data available early in project life times. Even in the best of circumstances, GCS systems will be subject to a large degree of uncertainty given that they involve geologic systems. To handle this uncertainty, we have developed specialized approaches to estimate and model fault intersection probability and probability of fault leakage. The approaches involve fault statistics and percolation theory with fuzzy rules, respectively.

The probability of CO_2 leakage via a fault is the product of the probability a plume will encounter a fault, and the probability of flow occurring across the fault where the seal is fully offset, or along the fault through the seal where the seal is not fully offset. We have described a way to estimate the former probability. The latter probability is dependent on the properties of the fault zone with respect to CO_2 flow (permeability, relative permeability, porosity, residual saturation, capillary entry pressure, etc.). The probability distribution of these properties is currently poorly constrained, and is a critical research area for GCS.

The fuzzy rule-based model component of the CF is used to estimate the probability (P_{leak}) of the plume intersecting a connected network of faults or fractures that also intersects a compartment in which impact may occur. The main computational effort of the approach lies in the numerical generation of the fracture networks. However, this only needs to be done once to provide the basis for constructing the fuzzy rules; predictive simulations are then performed very efficiently using these fuzzy rules. The uncertainty of P_{leak} is predicted by propagating the uncertainty in the input parameters. The method can be extended to apply to brine leakage risk by using the size of the pressure perturbation above some cut-off value as the effective plume size. The method can also be extended to account for non-random fault/fracture orientations, stratigraphic connections between faults/fractures, and three rather than two spatial dimensions. Confirmation and verification of these methods will have to await further field testing and demonstration projects focused on evaluating fault and fracture leakage processes.

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